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Final Report

Spectral Characteristics of Infrasonic Waves and Related Seismic Research

Period Covered: 1968, September 15, to 1971, September 30

RAMON CABRE S. I.

November 1971

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13. ABSTRACT

The infrasonic array at Peñas, La Paz, was enlarged from 4 to 7 microbarographs with an asymmetric disposition, covering an area of about 250 km^2; a digital recorder and an electronic integrator were added; French portable microbarographs were used for comparison and supplementary experiments. Acoustic and seismic data obtained was used for research at Observatorio San Calixto and at different research centers in the United States. Spectral analysis and correlations were made for relevant acoustic and seismic signals and infrasonic noise; from them, the following values could be calculated (mainly through computing programs): azimuth of arrival signals; incoherence of noise by coupling between solid earth and atmosphere; structure of the crust near La Paz; seismic energy liberation in the region for P seismic waves; earthquake focal mechanism. Some other aspects of seismicity were studied prospecting for earthquake prediction.

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OBSERVATORIO SAN CALIXTO

La Paz - Bolivia

Final Report

Period Covered: 1968, September 15, to 1971, September 15.

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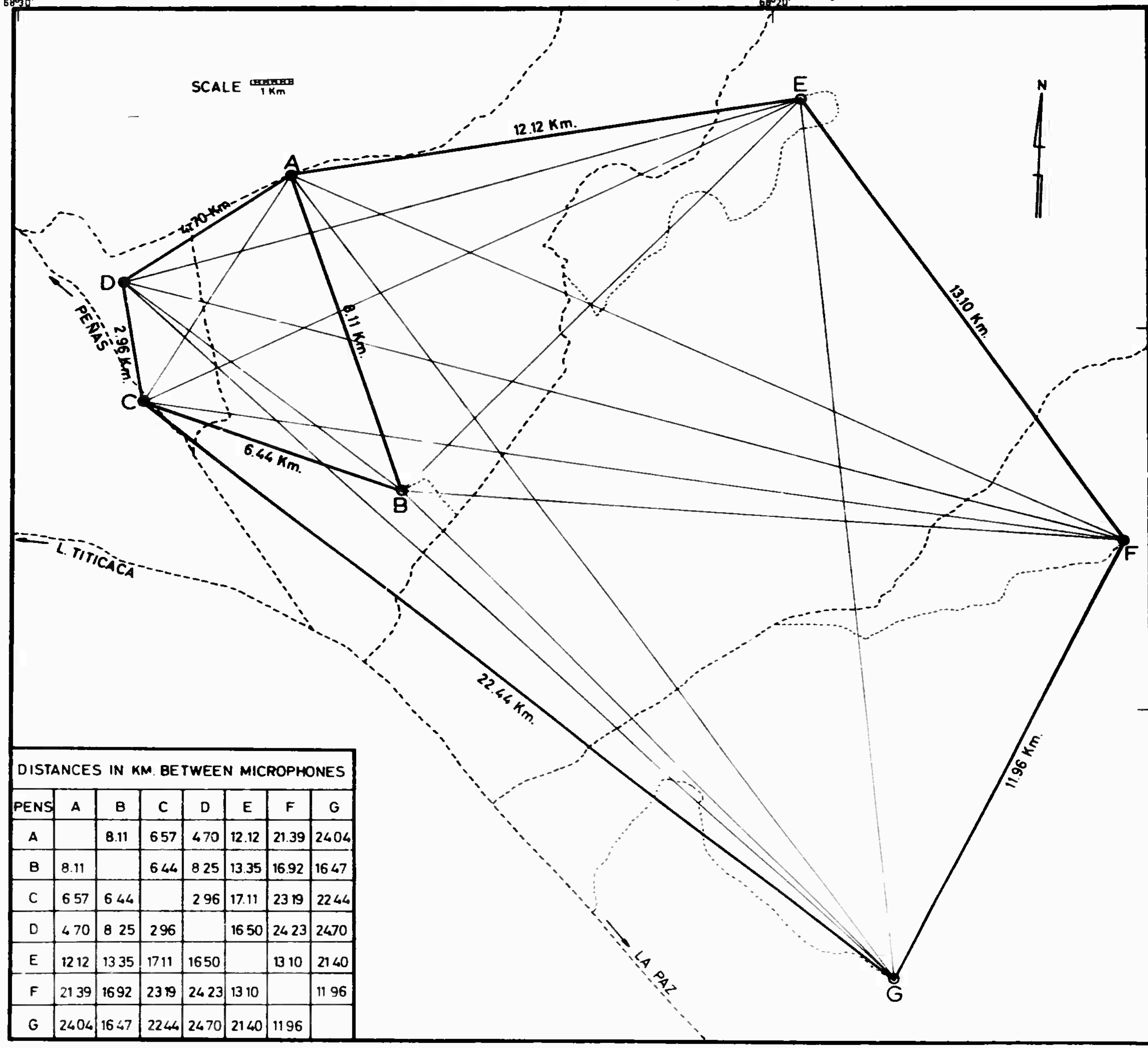
PEÑAS INFRASONIC ARRAY (JULY 1970)



DISTANCES IN KM. BETWEEN MICROPHONES							
PENS	A	B	C	D	E	F	G
A		8.11	6.57	4.70	12.12	21.39	24.04
B	8.11		6.44	8.25	13.35	16.92	16.47
C	6.57	6.44		2.96	17.11	23.19	22.44
D	4.70	8.25	2.96		16.50	24.23	24.70
E	12.12	13.35	17.11	16.50		13.10	21.40
F	21.39	16.92	23.19	24.23	13.10		11.96
G	24.04	16.47	22.44	24.70	21.40	11.96	

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INTRODUCTION

The work statements of this Grant provide for studies of atmospheric and seismic phenomena.

Records obtained in a geophysical station previously installed at Peñas, 55 km distant from La Paz, were a good basis for both observation of interesting phenomena and research. Peñas Station consisted of a microbarographic array of four elements and a teleseismic station with a LRSM-type seven elements array.

It was proposed to improve instrumentation in the following way:

a) Expansion of the microbarographic array with three new outposts in a spiral disposition.

b) Installation of a radio-telemetry equipment for transmitting both acoustic and seismic data from at least five distant sites, and its power generators.

c) Digital recording at the field central station.

d) A first class weather station to study the influence of meteorological conditions on acoustic signals.

The Grant Operation had shown the convenience of further improvements:

e) Completion of an energy integrator for the four operating microbarographs.

f) An analog computer for automatic detection and locating infrasonic signals.

g) Wind-driven power generators to feel telemetric kits in order to avoid some problems resulting from resupplying butane, given those hardly accessible sites (moreover, it is not a pure butane but a gas mixture, and still the distribution is

not quite regular in town).

The purpose of the above plan was to improve quality of recorded data and consequently to improve the research done both at the ERL Geoacoustics Laboratory (where magnetic tape records are systematically sent to) and at Observatorio San Calixto. A closer cooperation with a similar project in Huancayo (Peru) was envisaged but it was not actually feasible.

The following specific investigations were proposed:

a) Spectrograms and frecuency characteristics related to the different acoustic signals.

b) Location and identification of acoustic signals sources.

c) Attenuation factor of infrasonic waves with distance.

d) Spectral characteristics of acoustic noise.

e) Transfer functions of seismic waves for different crustal models.

f) Some problems on seismicity in the Central Andes.

g) Correlation of seismic and infrasonic waves.

That research in a large extent had to be accomplished through the preparation of memorias required by the Universidad Mayor de San Andrés, La Paz, Bolivia, to obtain the Geological Engineering Degree (Mention in Geophysics), under the guidance of senior scientific personnel.

The above program appears now too ambicious and partly could not be filled by different reasons: a part of the instruments supposed to be forwarded independently of the Grant did not arrive; local difficulties prevented the completion of another part of the instrumentation assumed to be designed and assembled within the project; the lack of similar installations in the neighbour areas resulting in a scarcity of data to be correlated with that obtained at Peñas... Nevertheless most of tasks were accomplished quite satisfactorily as shown below.

The work is going to be continued after the expiration of this Grant. Therefore, some investigations are still running and are considered of interest for future research.

PART I. INSTRUMENTATION.

a) Three microbarographs received on May 22, 1970 were installed at larger distances from the central recording place than the four previously existing ones. Some details had to be revised and immediately they were installed. They were located at higher altitudes with direct sight to the central field station (Figure 1).

At such remote, isolated sites it was impossible to obtain a complete safety and intruders damaged in fact the installations in site E, so it stopped running; a bunker style housing was built at the end of winter, actually at the end of this grant.

b) Radio telemetry for permanent transmission of data to the central station was installed at the three new out - posts; power for transmitters is obtained through butane thermoelectric generators. No other equipment was obtained, so problems encountered in cable lines from the ancient outposts could not be avoided.

c) A digital recorder D-1 with its complementary encoders, etc. was installed. A short circuit apparently produced during transportation ruined a few electronical parts which have been replaced; another output damage was more difficult to be located; a flexure of an axis which finally could be found and provisorily repaired, so that it was operational on June 1971; that part will also be replaced in the future.

d) The proposed weather station could not be established as expected; only some old instruments available at Observatorio San Calixto were installed; so temperature, humidity, pressure and precipitation were permanently measured during the last years; but only a few measurements of wind could be obtained.

e) An electronic integrator prepared by the Station Manager, to measure in line energy arriving to the four old microbarographs, was completed and soon became operational;

it is a very useful means to discover signals recorded in microbarographs and to estimate their size.

f) An analog computer to measure in line intensity, direction and horizontal velocity of coherent signals crossing the acoustic array was designed and constructed by the Station Manager, Eng. Flores, but he was too occupied on other problems and could not yet finish the tests for this complete device; its description will be reported to AFOSR as soon as it will be finished.

g) A wind battery charger was designed and constructed to substitute butane gas generators, but some modifications should be performed after testings. It is expected that it will operate in a few months after expiration of this Grant.

Every remote outpost constantly needs 10 watts (transmitter, 7; field alternator, 2; calibration circuitry, 1) and only momentarily 2 more watts for valve motor and calibration motor which may be neglected.

Considering the threshold of wind speed to move a windmill connected to a car alternator at 4 m/sec., and that this speed is obtained in the area during at least 2 hours per day, the whole device was conceived for this minimum requirement; the tests done advised for some mechanical changes.

When this wind-driven generator will be definitively installed, its description will be reported to AFOSR.

Heavy storms have disturbed at different times some instruments, especially the six galvanometers of the seismic array; its function has been stopped since on the other hand its aperture was too narrow; but the six seismometers of the central site have been maintained in operation all the time.

During April 1970, two microbarographs French made (at the Laboratoire de Physique - Ecole Normale Supérieure,Université de Paris) were tested against the American ones operating at Peñas (the tests are recorded on magnetic tape available at ESSA Office); French equipment appeared to be portable, low power consuming, reliable, but not giving so much of informations as Ame-

rican equipment.

Later on, different tests were made for the noise at different sites and levels for American and French equipments both using and without antennas, looking for its coherence at different distances, etc. Noise produced nearby is better recorded if pipe antennas are not used, what means that antennas are reducing noise produced nearby. The study of these records is not yet finished until; the distance of 30 m. gives the minimum of coherence (maybe at the end of the study this minimum will go down to 20m).

Another test was conducted by running one of the French microbarographs at Santa Cruz (63°11'W, 17°48'S; 420m asl.) during part of July 1971, for comparison, and records are being studied; the other one is still operating for long range comparisons near the C American one.

PART II. ACQUISITION OF DATA.

Both acoustic and seismic instruments have correctly worked along all the time this Grant lasts with no substantial interruption. Every analog and digital magnetic tape record obtained has been sent to the ERL Laboratory for further analysis

Esterline-Angus records for the atmospheric nuclear explosions have been copied and were sent together including magnetic tape records to the ERL Laboratory. Nuclear atmospheric explosions are the most conspicuous events recorded. See a sample in Figures 2 to 4.

Some other remarkable acoustic records were obtained on May 21, 1969 at 01h05m GMT for the Fernandina Island, Volcano explosion and different big earthquakes (for instance the Iberian Peninsula earthquake of magnitude 7.8-8, on February 28, 1969); for the later, the acoustic waves were produced by coupling seismic surface waves and atmospheric pressure oscillations. Finally, meteorological storms frequently produced outstanding trains of long-period waves.

On the other hand, a total of almost 20,000 earthquakes were recorded during the three years operation under the AFOSR Grant. The main data was daily sent to the National Oceanographic and Atmospheric Administration; revised and completed data is included in bulletins and distributed to the pertinent Bureaux; reproductions of records are often sent to investigators upon request.

Through publications it appears that both acoustic and seismic data is used for different research purposes, for instance Pomeroy and Johnston in the final report of Contract No. F44620-69-C-0085 (June 1971) inform about a correlation between seismic and microbarometric traces.

PART III. RESEARCH.

Auto-correlation and cross-correlation were applied to the analysis of both signals and noise, especially for coupling solid earth and atmosphere when strong seismic waves arrive.

Spectral analysis is practiced for all relevant signals to obtain both cross-spectrum and energy-spectrum. Those are considered instrumental for many investigations. Events originated in point sources show a large coefficient of coherence all along the wave trains. Surface sources, as those generated by large earthquakes, produce waves much less coherent and only for a short time.

The methods used do not differ substantially from those presented by Pomeroy and Johnston (1971): Correlation of Infrasonic Microbarometric Disturbances and Long Period Seismic Phenomena (Final Report of Contract No. F44620-69-C-0085). See a sample in Figure 5.

In this way, apparent velocity of acoustic waves transmitted through the high atmosphere (according to velocities at high altitudes) and their approach directions could be measured. Signals from the East arrive in a very steady direction; on the contrary, signals arriving from the North, for example those

produced by the nuclear explosion of December 28, 1968 in China, fluctuated very rapidly in direction (Figure 6).

Also through these correlations it was found that noise waves transmitted near the soil are entirely of local character, so waves detected at two points ten meters distant are practically incoherent.

Infrasonic noise characteristics: The different characteristics of infrasonic noise at a given site are important to qualify the place from the point of view of infrasonic signals reception (Figure 7).

The energy plot of a typical noise sample from June 3 to June 4, 1969 (Figure 8) indicates the low level of infrasonic noise during the night at Peñas and how it increases during the day. The daily cycle of noise as function of time (Figure 9) indicates the low level of coherence of the infrasonic records in general. These coefficients of coherence were obtained considering the different periods of the power spectra and they represent the mean values of all the periods with their correspondent standard deviations.

Since infrasonic signals are very stationary, it is possible to remove the noise from them by means of correlation analysis. A significant dependance of the coefficient of coherence and the period of the noise may be noticed in Figure 10.

Seismic waves transfer functions were calculated through the earth's crust for different Andean crustal models, particularly considering dipping interfaces.

Different aspects of seismicity in the Central Andes were studied, especially regional strain release and activity related with Arica bent. The high activity of this region is evident through Figures 11 and 12.

PART IV. ORAL COMMUNICATIONS AND PUBLICATIONS.

Oral communications were presented to different meetings:

At the AGU meeting of 1969, L. Fernández S.I., associate investigator, reported studies on the records of December 18, 1968. Figures 2 to 6 are to show a part of those studies (they are samples of some analysis applied to different signals).

Also L. Fernández S.I. attended the AFOSR/ARPA Geoacoustics Program Review at Isotopes Headquarters in Westwood, N.L. on December 12 to 13, 1968. Under the title "Bolivian Array", he presented an analysis of the infrasonic waves generated by the thermonuclear explosion of August 24, 1968 in the Pacific.

J. Flores reported at the headquarters of ESSA, in 1969, to a group of investigators: "Propagation of Infrasonic Waves from China to Bolivia".

R. Cabré S.I., at the IUGG XV General Assembly: "Focal Mechanism of Earthquakes and South American Tectonism".

Publications consist partly in 13 Theses that have been presented to the Universidad Mayor de San Andrés (UMSA), La Paz:

Encinas, H. (1969). "Secuencias de Réplicas y sus Implicaciones Geológicas". A total of 154 aftershocks of Taltal (Chile) earthquake are recognized in a succession rapidly decreasing, so that the last one identified happened 4 months after the main shock (December 28, 1966); no aftershock could be recorded after the deep earthquake at the Peru-Brazil border (November 3, 1965).

Da Silva, G. (1969). "Sismogramas Teóricos y Funciones de Transferencia Producidos por Cortezas Buzantes". Using the Zoeppritz equations, interference of refracted and reflected P and S waves originated by P waves arriving to the crust was calculated. So transfer functions and theoretical seismograms were obtained corresponding to different crustal models (changing thickness and dip).

Antezana, R. (1969). "Composición Geofísica de la Estructura Cortical bajo los Andes Centrales". Through the phase-velocity dispersion of Rayleigh waves between Arequipa and La Paz, the following model (mean values) is obtained :

	Thickness (Km.)	Vp (Km/sec)	Vs (Km/sec)	Density (Gr/cm^3)
Sediments	4	3.98	2.38	2.34
Granitic layer	22	5.80	3.40	2.78
Basaltic layer	24	6.60	3.80	3.20
Upper Mantle		8.10	4.71	3.35

Between Antofagasta and La Paz:

Sediments	4	4.00	2.36	2.34
Granitic layer	19	5.80	3.40	2.78
Basaltic layer	18	6.75	3.90	3.20
Upper Mantle		8.20	4.75	3.30

Ibiett, A. (1969). "Análisis Espectral de la Corteza Terrestre en La Paz, mediante Ondas Sísmicas P de Corto Periodo". After calculating P-waves transfer functions for different crustal models and comparing them with spectra of ten earthquakes recorded at La Paz station, he considers the best fitting model for La Paz zone a crust of 72 km with a mean Vp of 6.2 km/sec.; but he remarks that this method needs refinements to become safely dependable.

Rodriguez, F. (1970). "Influencia de la Atmósfera en las Oscilaciones del Subsuelo". He shows that the noise is minimum at night until about 8 o'clock, and then increases gradually until a maximum between 12 and 13 o'clock, being the extreme amplitude values about 0.01 and 10 square microbars. Changes of noise level are well correlated with temperature changes. The energy of noise generally increases with its period but a maximum of ex-

citation was noticed between 12 and 15 seconds of period and another between 600 and 800 seconds. Noise of 200 to 1,000 seconds of period is more stationary than noise of 1 to 100 seconds. Velocity of noise is that of atmospheric fronts for long period, that of waves whirlwinds for short period waves. The correlation between atmospheric and seismic noises shows that each millibar pressure originates an amplitude of about 0.1 microns for periods of 6 to 60 seconds; on the other hand microseisms of 10 microns with period of 4 seconds originate a pressure oscillation of 1 millibar.

Castañón, W. (1970). "Distribución Espacial y Liberación de Energía Sísmica en la Costa Central del Pacífico Sudamericano". Seismicity of Central West South America is analysed according to the 1433 earthquakes located by the U.S. Coast and Geodetic Survey during 1963 through 1968. Strain release for layers 100 km thick is plotted and related to the theory of moving plates paving the earth. Seismic trends are envisaged through polynomial approximation; residuals or anomalies during the period considered (related to these trends) are plotted.

Tellería, J.L. (1970). "Dinamismo Sísmico bajo los Andes Centrales y la Tectónica Global". He founds in all the six events of the Western South American Coast studied that a double couple mechanism explains the data analysed. Pressure axis are perpendicular to the coast; movement axis have the same direction, but reverse faulting in shallow shocks, with normal faulting in intermediate and deep shocks. All that agrees with the hypothesis that a lithospheric plate coming from the East Pacific Rise bends down and is reabsorbed underneath the continent. This plate seems

to be 120 km thick and to dip 35°to 40°until a depth of 500 km, where dipping suddenly increases to about 75°. Apprently this plate has two movements: counter-clockwise rotation and translation pushed from the East Pacific Rise, where sea floor would be spreading.

Mendoza, E. (1970). "Atenuación de Ondas P de Corto Período en los Andes Centrales". It is a preliminary study confirming that the roots of the Andes absorbs abnormally seismic energy.

Cosulich, J. (1970). "Optimización de un Arreglo de Detectores de Infrasonido". Assuming that monochromatic wave trains arrive to an array of sensors, the influence of number and disposition of sensors to obtain apparent velocity and the arrival azimuth is studied through cross-correlation methods. Conclusions are: Solution will be much better as the number of sensors will be higher; the disposition of sensors should be as much asymmetrical as possible; the minimum separation of sensors should be limited by the values $\lambda/_3$ and 2λ. The method is applied to a microbarographic signal recorded at Peñas (Figure 6)

Amador, J. (1970). "Estudio de Ondas Infrasónicas Producidas por Causas Naturales y Artificiales". Surface waves of 30 to 40 sec period with an amplitude of one micron generate infrasonic waves of 1.5 to 3.2 microbars. The group velocity of these waves equals the group velocity of originating seismic waves; no atmospheric waves generated by earthquakes were found with sound velocity; on the contrary, volcanic and artificial explosions as point sources generate infrasonic waves, mainly those of the fundamental mode and acoustic-gravity one (the later mentioned waves with some dispersion) propagating at sound velocity; attenuation with distance is really small.

González, R. (1971). "Sismicidad Local en la Parte Central de Sudamérica". Assuming that some earthquakes release a certain amount of accumulated energy until a distance of 1,000 km (as a function of focal depth and distance) this energy for different towns is plotted versus time in cumulative form; if an interval long enough is considered, the graph may be inscribed between two parallel lines each other as separate as the maximum energy plot-

ting approaches the lower line, a large earthquake may be expected in the town (the author recognizes that the interval studied was too short; therefore the method is being applied to a longer time).

Escóbar, G. (1971). "Ondas Infrasónicas: Ruído y Señales Observadas en la Estación Geofísica de Peñas". He continues the work of Amador (1970), local air turbulence and temperature changes are the main sources of infrasonic noise, mainly for long period records; so it is advisable to emphasize the analysis of short period records rather than the long period ones. The infrasonic waves produced by a remote atmospheric nuclear explosion cannot produce any strong motion of the solid earth; so the French explosion of May 30, 1970 produced an oscillation of 24.1 microbars at Peñas which could induce an oscillation of solid earth of only 0.0048 microns.

Lejsek, J. (1971). "Mecanismo Focal de Terremotos y el Tectonismo Sudamericano". Twelve focal mechanisms are presented in the Easter Island region and in the South American Continent, in spite of a rather short quantity of data. The maximum compressive stress appears almost perpendicular to the coast with some trend to turn clockwise in the continent, but with no apparent trend in the Easter Island region.

Other papers:

Flores, J. (1968)."Infrasonic Energy Autocorrelator". Publication of Observatorio San Calixto.

Fernández, L., Flores, J. and Cosulich, J. (1968)."Infrasonic Acoustic Waves Generated by the Thermonuclear Explosion of August 24, 1968". Publication of Observatorio San Calixto.

Fernández, L. and Santa Cruz, J. (1969)."Small Sequence of After Shocks in the Andean Valley of Zongo". Earthquake Notes 40, pp. 27-48.

Fernández, L., Da Silva, G. and Careaga, J. (1969)."Influence of a Dipping Crust on the Spectrum of P Seismic Waves". Geofísica Internacional, México, 9, pp. 21-28.

Cabré, R. (1971)."Ondas Lg registradas en La Paz, Bolivia". Geofísica Panamericana (in press).

Tellería, J.L. (1971)."Fuerzas y Esfuerzos Tectónicos bajo los Andes Centrales". Geofísica Panamericana (in press).

Cabré, R., Rubín de Celis, J. and Flores, J. (1971)."Some Notes on Discrete Trains of Infrasonic Waves Produced by Point Sources". Geoph.Jour. Royal Astr. Soc. (in press).

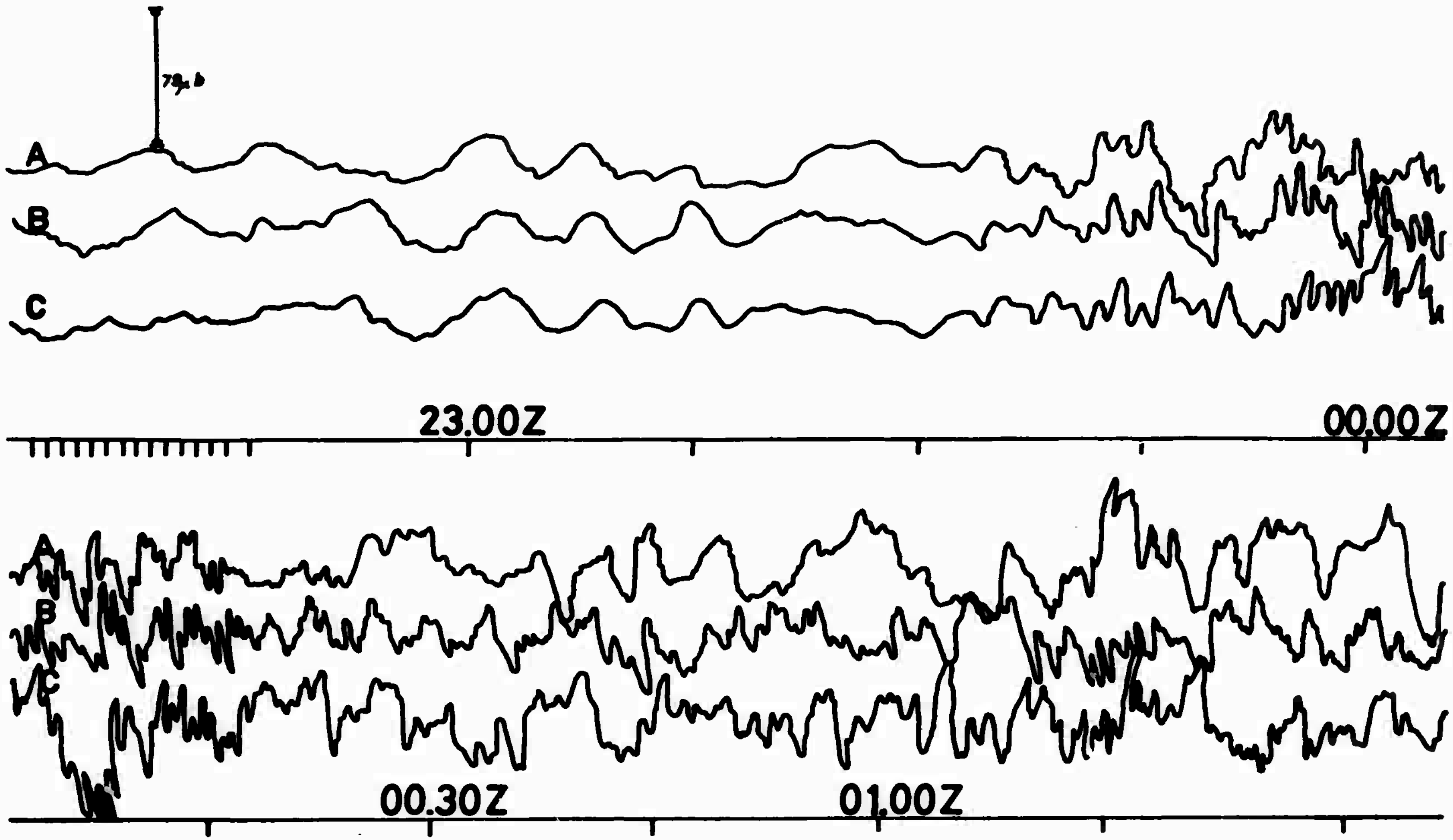

Figure 2. Long-period records corresponding to the arrival of waves produced by the event of December 28, 1968.

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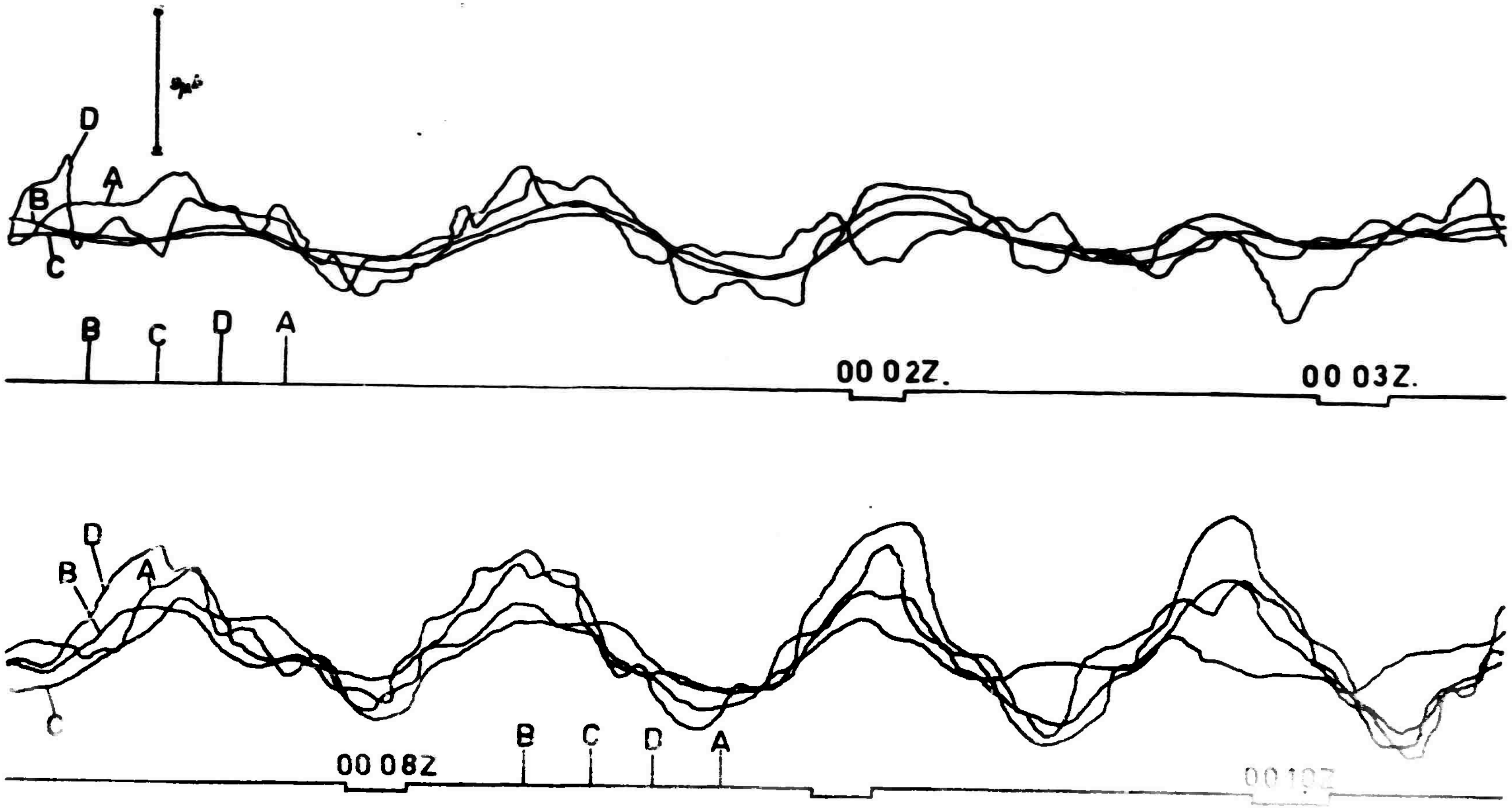

Figure 3. Short-period records showing the same event as fig. 2.; they are superposed to show coherence and time lag.

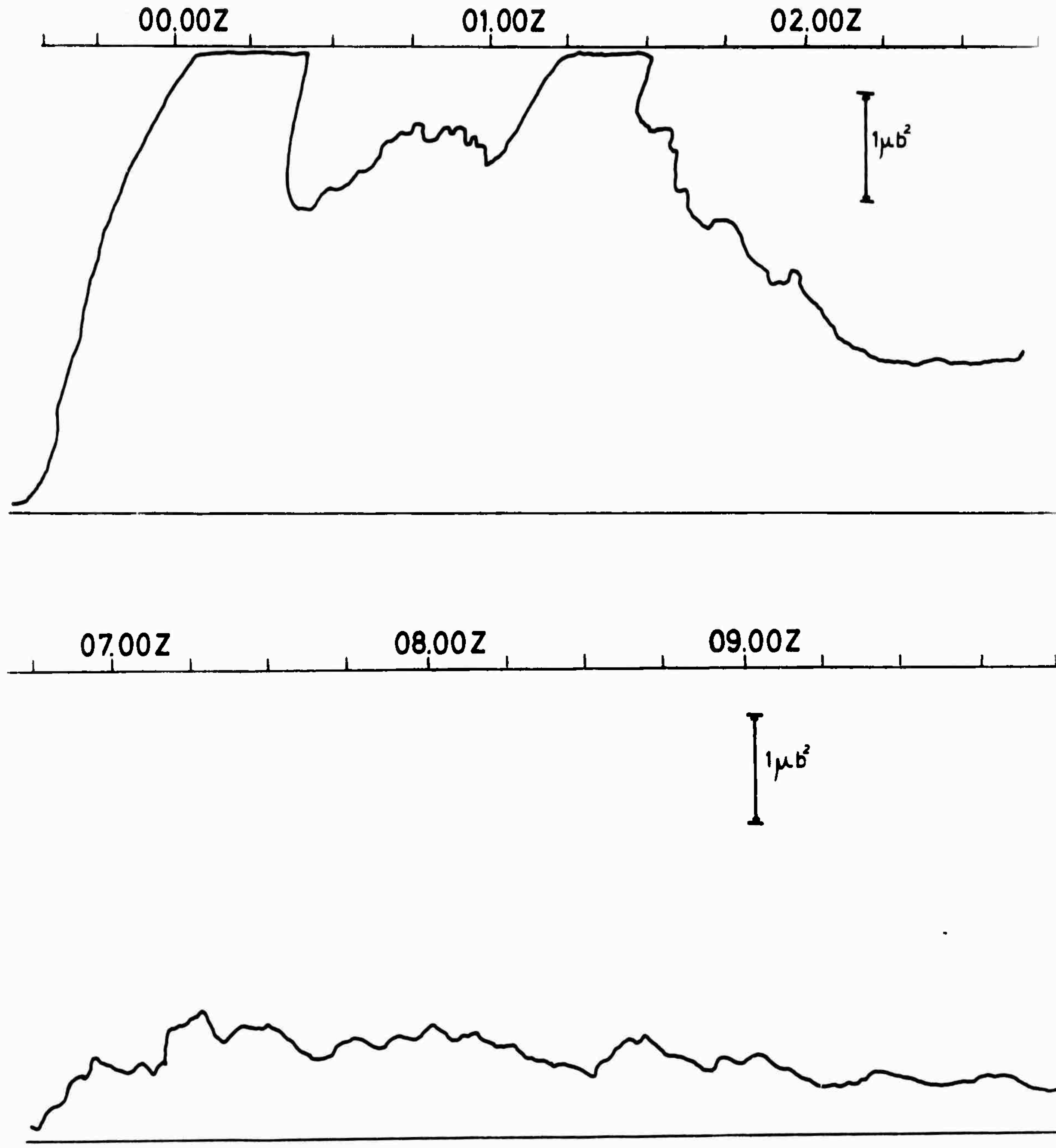

Figure 4. Integrated energy records of the first (upper) and second (lower) arrivals corresponding to the same event as fig. 2.

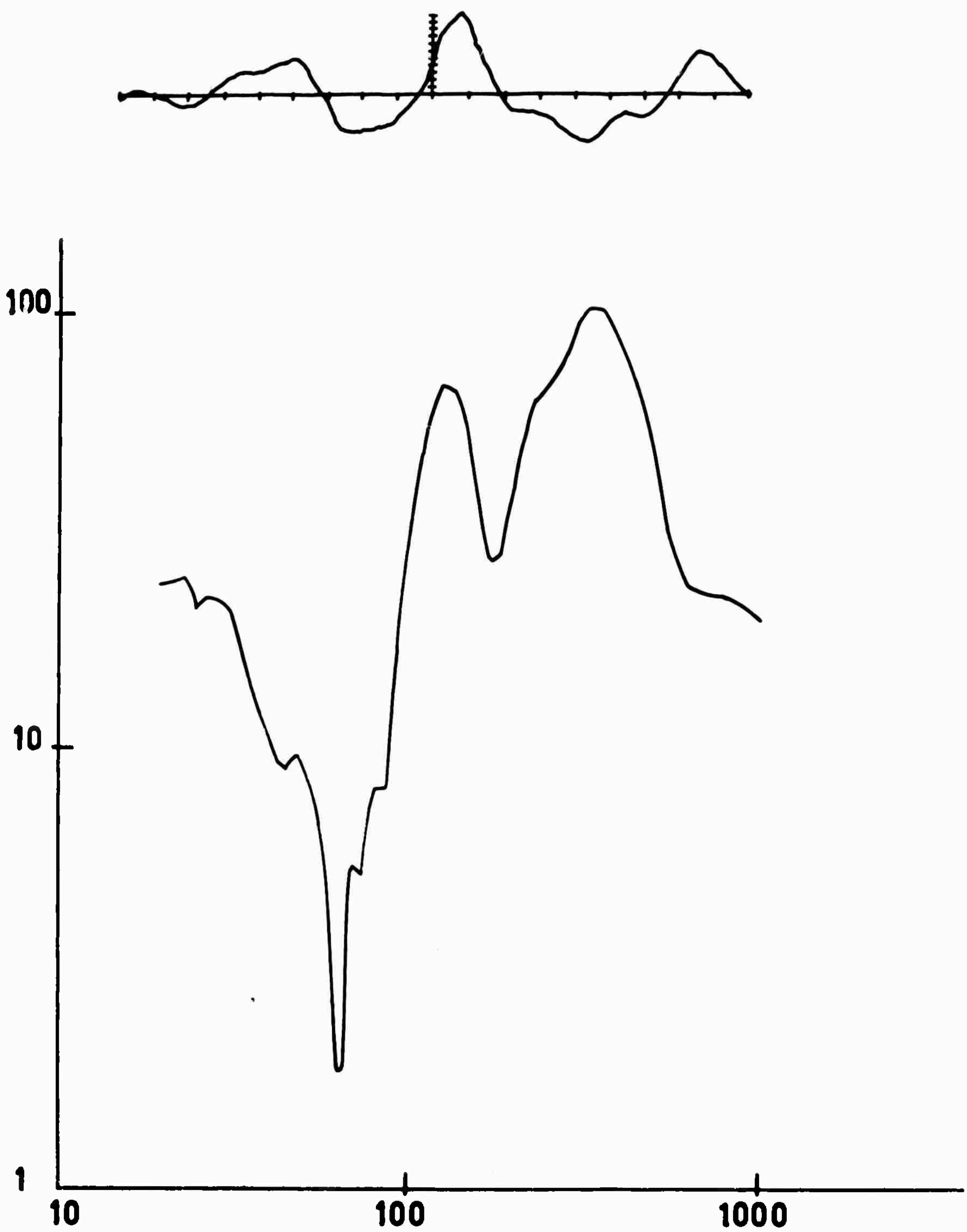

Figure 5. Sample of crosscorrelation and its Fourier spectrum. It corresponds to the interval between 23h30m and 24h46m on December 28, 1968.

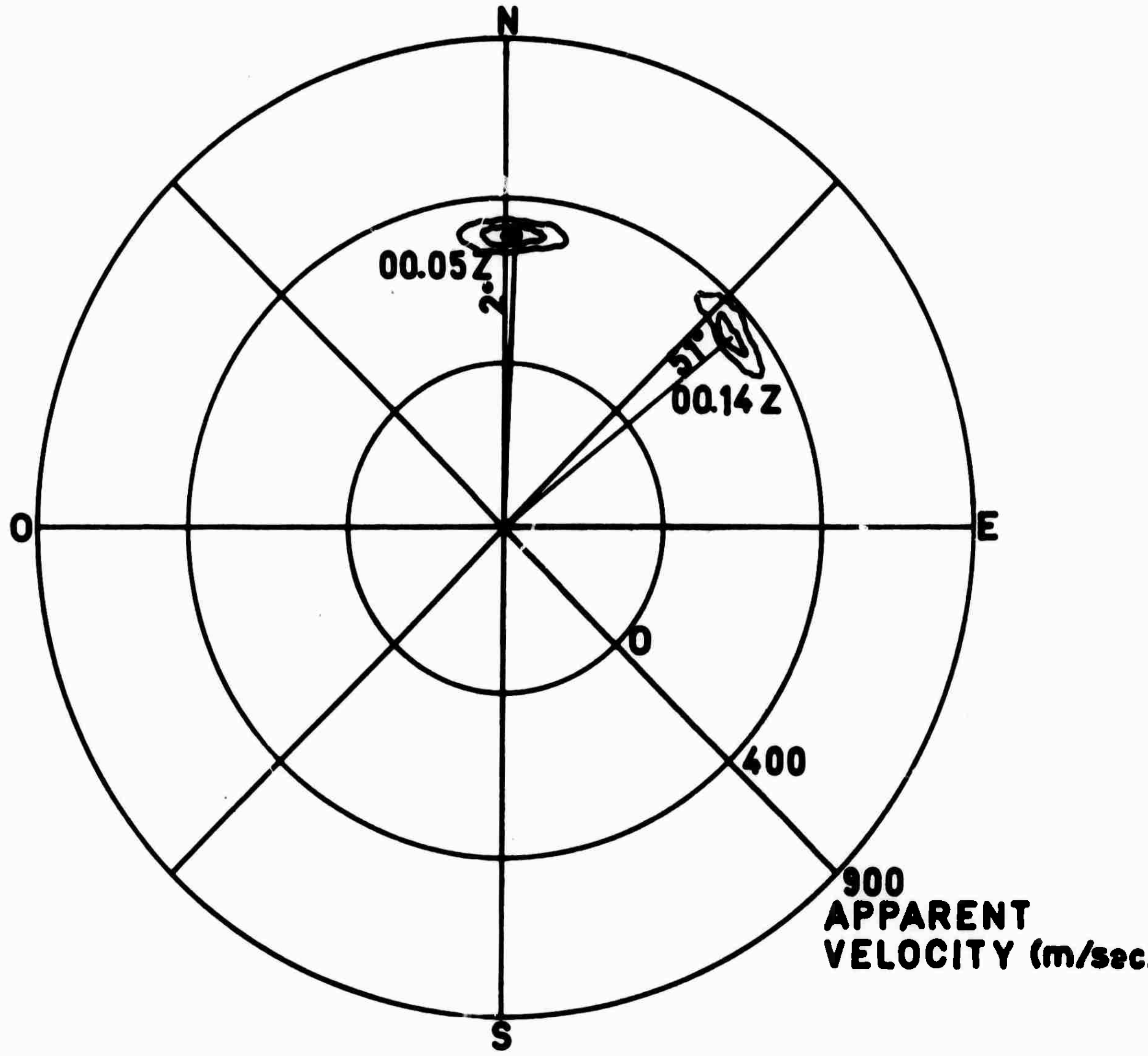

Figure 6. Sample of directional analysis at two moments of the signal exhibited in fig. 3.

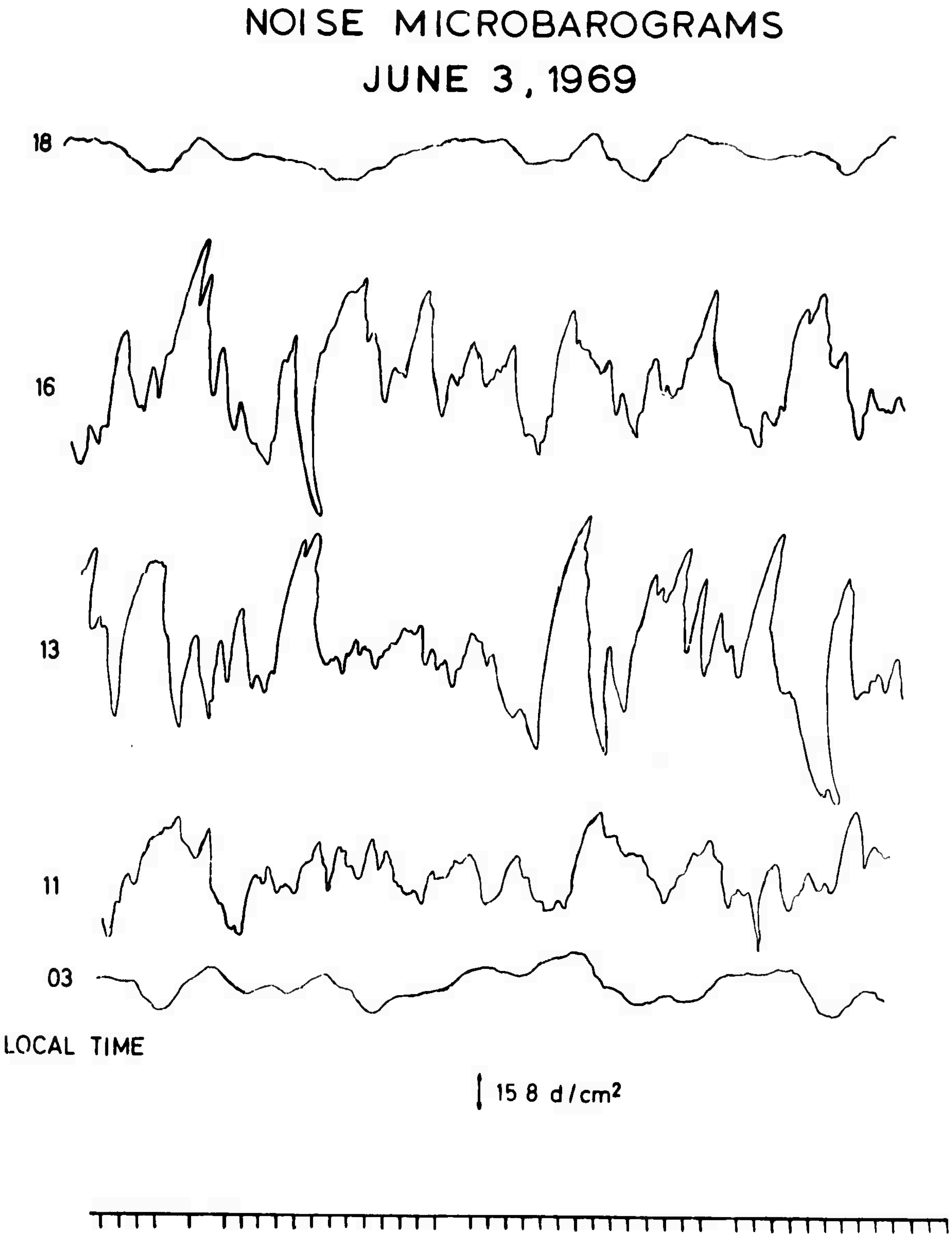

Figure 7. Samples of the original microbarograms indicating the level of noise at Peñas at different hours of the day

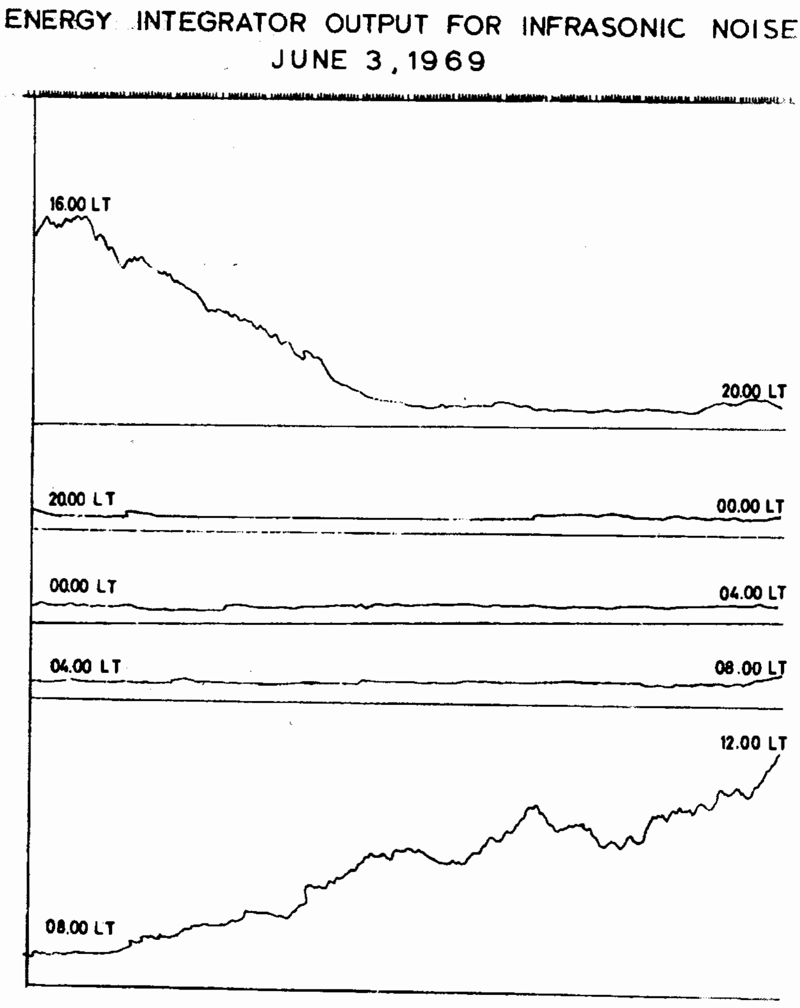

Figure 8. Output of the energy integrator indicating in relative units the changes of background noise along the 24 hours of one day (local time).

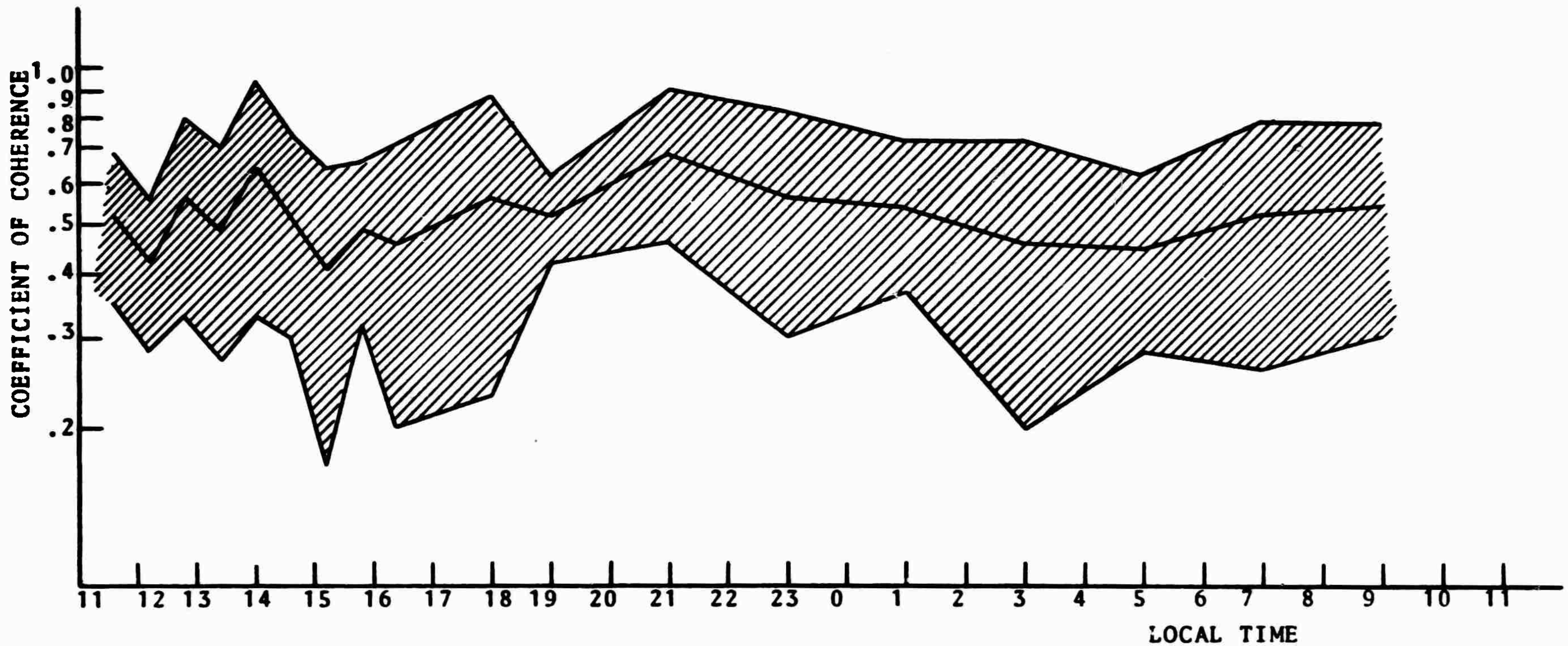

Figure 9.- Coefficient of coherence between microbarograms of noise obtained at the same site and at different hours of the day. Peñas, June 3,4, 1969. Mean values and standard deviations for different periods of the power spectra.

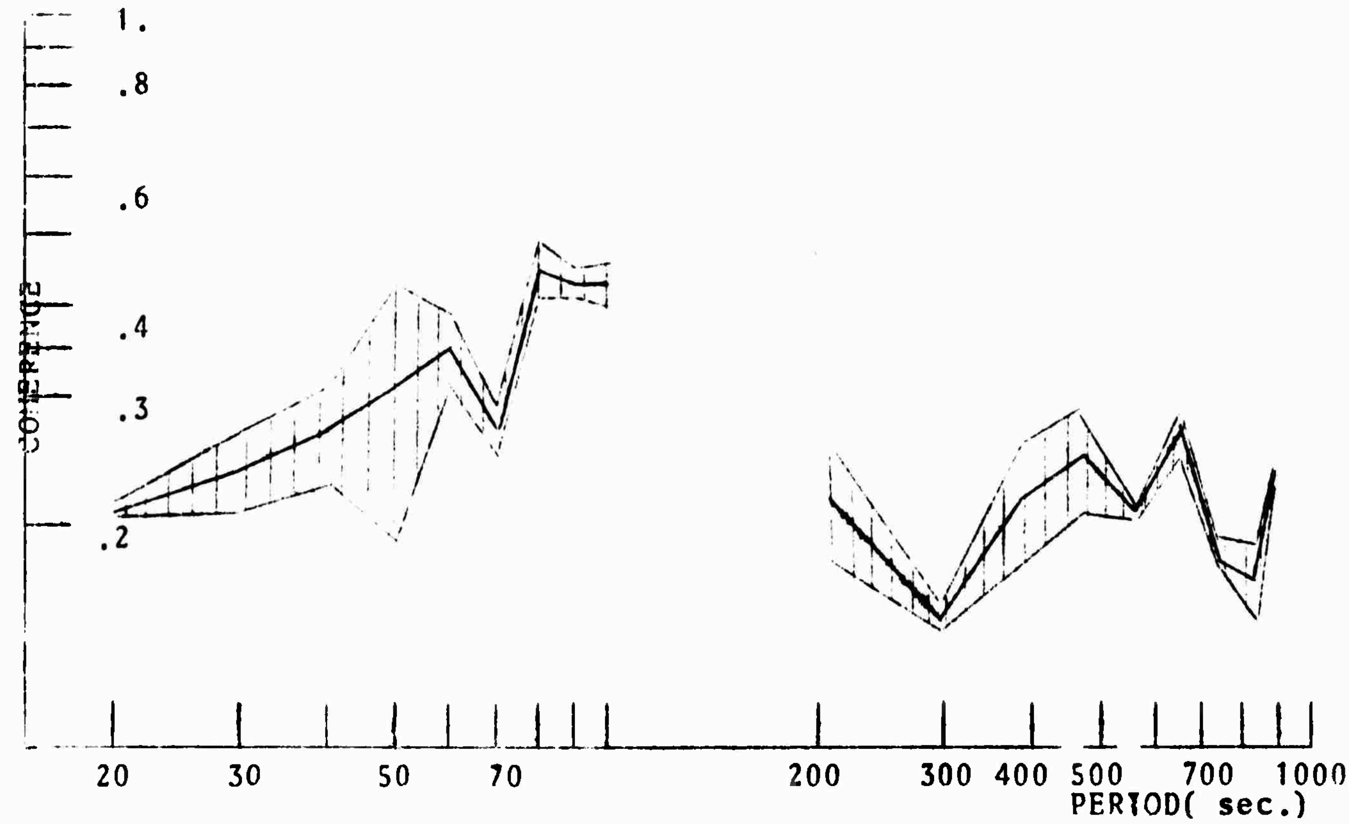

Figure 10. Coherence of infrasonic noise as a function of period for six sifferent separations of instruments, long and short-period microbarograms. Mean values and standard deviations.

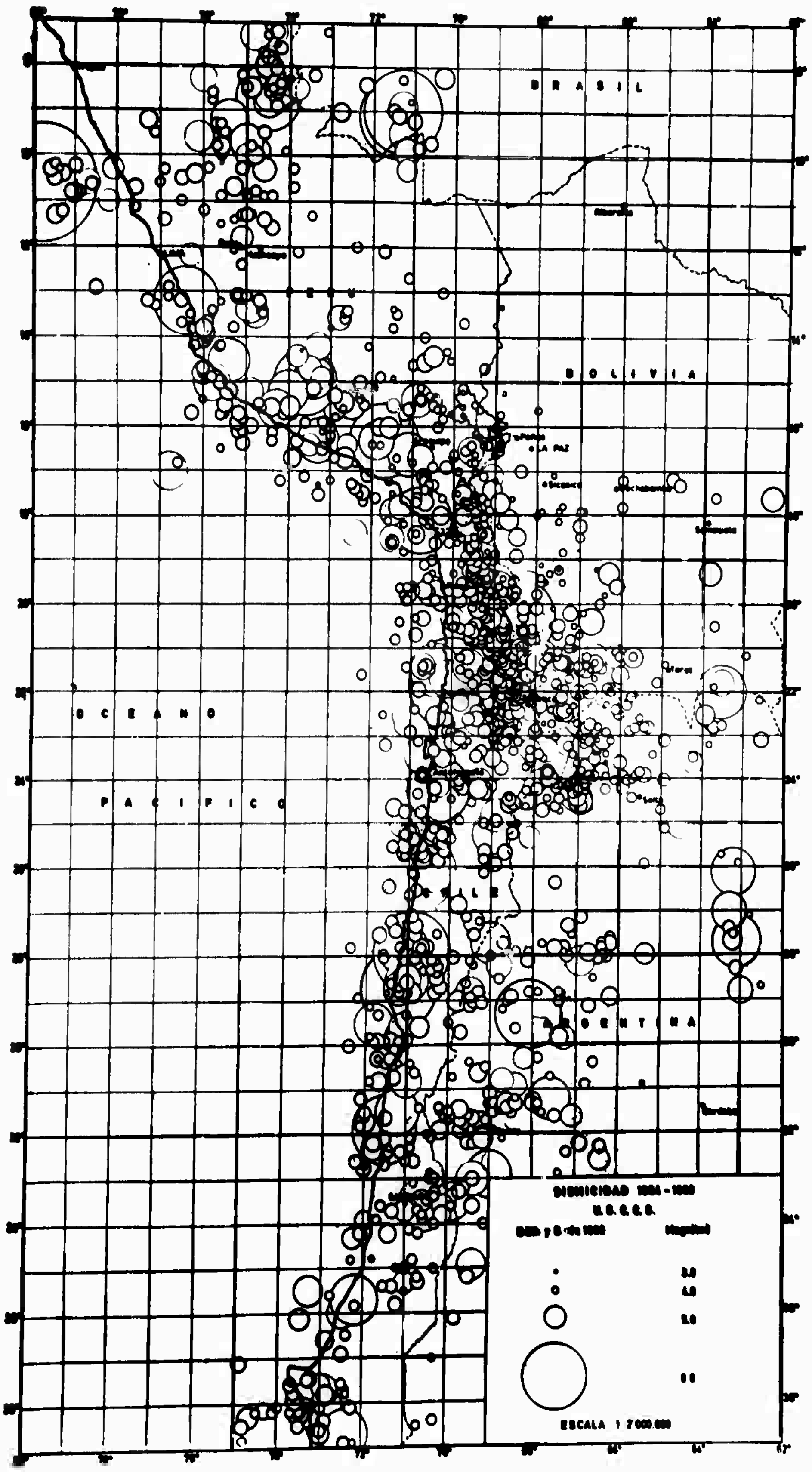

Figure 11. Epicenters of earthquakes located by the USCGS for the period 1964-1968. Magnitude is indicated by the size of the circle according to Båth-Duda area law.

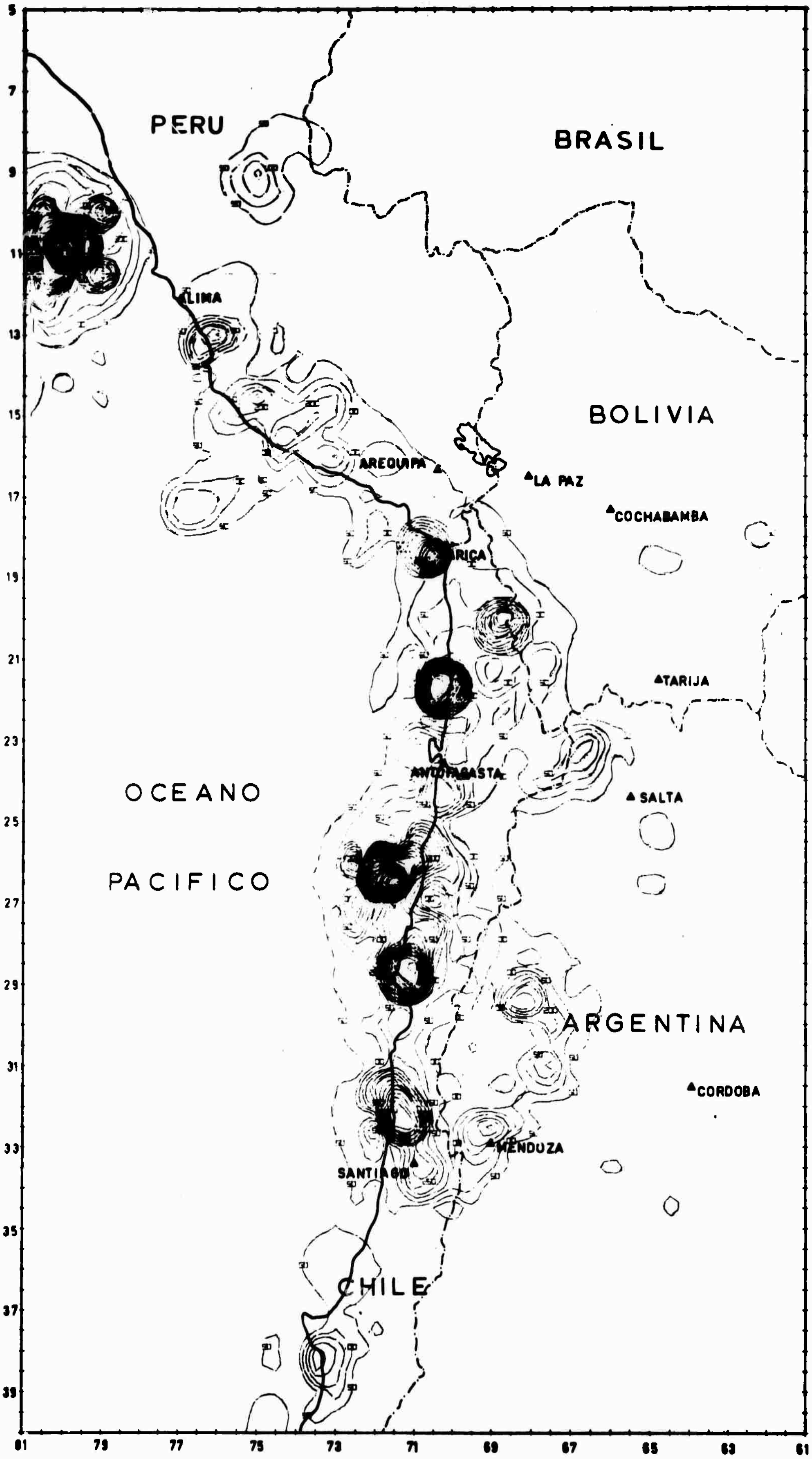

Figure 12. Lines of equal strain rèlease by earthquakes during the period 1964-1968. Units in ergs x 10^7 .